Overview and Recent Accomplishments of Advanced Mirror Technology Development (AMTD) for Very Large Space Telescopes

H. Philip Stahl, MSFC

AMTD is a funded NASA Strategic Astrophysics Technology (SAT) project

SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2013

Top Level

Most future space telescope missions require mirror technology.

Just as JWST's architecture was driven by launch vehicle, future mission's architectures (mono, segment or interferometric) will depend on capacities of future launch vehicles (and budget).

Since we cannot predict future, we must prepare for all futures.

To provide science community with options, we must pursue multiple technology paths.

All potential UVOIR mission architectures (monolithic, segmented or interferometric) share similar mirror needs:

• Very Smooth Surfaces	< 10 nm rms
• Thermal Stability	Low CTE Material
• Mechanical Stability	High Stiffness Mirror Substrates

AMTD Objective

Our objective is to mature to TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

This technology must enable missions capable of both general astrophysics & ultra-high contrast observations of exoplanets.

To accomplish our objective,

- We use a science-driven systems engineering approach.
- We mature technologies required to enable the highest priority science AND result in a high-performance low-cost low-risk system.

AMTD Team

AMTD uses a science-driven systems engineering approach which depends upon collaboration between a Science Advisory Team and a Systems Engineering Team.

We have assembled an outstanding team from academia, industry, and government with extensive expertise in

- UVOIR astrophysics and exoplanet characterization,
- monolithic and segmented space telescopes, and
- optical manufacturing and testing.

AMTD Project Technical Team

Principle Investigator			**Systems Engineering**	
Dr. H. Philip Stahl	MSFC		Dr W. Scott Smith	MSFC
Science Advisory			**Engineering**	
Dr. Marc Postman	STScI		Laura Abplanatp	Exelis
Dr. Remi Soummer	STScI		Ron Eng	MSFC
Dr. Arund Sivaramakrishnan	STScI		William Arnold	MSFC
Dr. Bruce A. Macintosh	LLNL			
Dr. Olivier Guyon	UoAz			
Dr. John E. Krist	JPL			
Integrated Modeling			**AMTD-2 Proposal**	
Gary Mosier	GSFC		Tony Hull	Schott
William Arnold	MSFC		Andrew Clarkson	L3-Brashear
Anis Husain	Ziva			
Jessica Gersh-Range	Cornel			

Funding

NASA ROSES SAT (10-SAT10-0048)

Space Act Agreement (SAA8-1314052) with Ziva Corp

NASA Graduate Student Research Program (NNX09AJ18H)

Heritage

AMTD builds on over 30 yrs of US Gov mirror technology development:

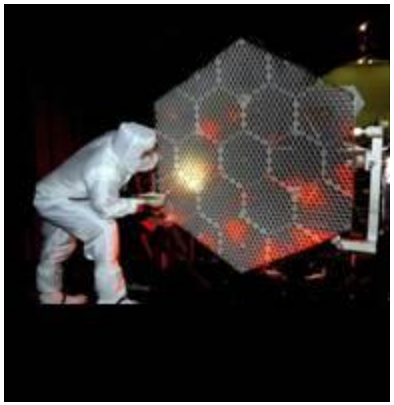
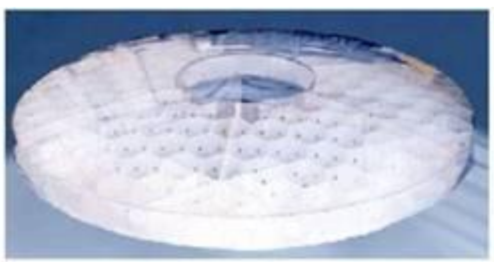
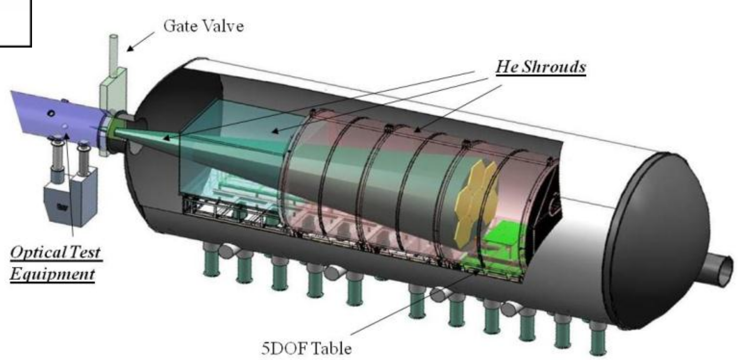


Figure 3-7: LAMP (left), AOSD (center) and SMT (right)



ITT's 2.4m ATT Demonstration Mirror



AMTD Team

Science & Engineering work collaboratively to insure that we mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

- derive engineering specifications for monolithic & segmented mirrors which provide on-orbit science performance needs AND satisfy implementation constraints
- identify technical challenges in meeting these specifications,
- iterate between science needs and engineering specifications to mitigate the challenges, and
- prioritize technology development which yields greatest on-orbit performance for lowest cost and risk.

STOP (structural, thermal, optical performance) models are used to help predict on-orbit performance & assist in trade studies.

Tasks

Derive engineering specifications for a future monolithic or segmented space telescope based on science needs & implementation constraints.

Mature 6 inter-linked critical technologies.

- *Large-Aperture, Low Areal Density, High Stiffness Mirrors:* 4 to 8 m monolithic & 8 to 16 m segmented primary mirrors require larger, thicker, stiffer substrates.
- *Support System:* Large-aperture mirrors require large support systems to ensure that they survive launch and deploy on orbit in a stress-free and undistorted shape.
- *Mid/High Spatial Frequency Figure Error:* A very smooth mirror is critical for producing a high-quality point spread function (PSF) for high-contrast imaging.
- *Segment Edges:* Edges impact PSF for high-contrast imaging applications, contributes to stray light noise, and affects the total collecting aperture.
- *Segment-to-Segment Gap Phasing:* Segment phasing is critical for producing a high-quality temporally stable PSF.
- *Integrated Model Validation:* On-orbit performance is determined by mechanical and thermal stability. Future systems require validated performance models.

Philosophy

Simultaneous technology maturation because all are required to make a primary mirror assembly (PMA); AND, it is the PMA's on-orbit performance which determines science return.

- PMA stiffness depends on substrate and support stiffness.
- Ability to cost-effectively eliminate mid/high spatial figure errors and polishing edges depends on substrate stiffness.
- On-orbit thermal and mechanical performance depends on substrate stiffness, the coefficient of thermal expansion (CTE) and thermal mass.
- Segment-to-segment phasing depends on substrate & structure stiffness.

We are deliberately pursuing multiple design paths to enable either a future monolithic or segmented space telescope

- Gives science community options
- Future mission architectures depend on future launch vehicles, AND
- We cannot predict future launch vehicle capacities

Key
Done
Stopped
In-Process
Not Started Yet

Goals, Progress & Accomplishments

Systems Engineering:

- **derive from science requirements monolithic mirror specifications**
- **derive from science requirements segmented mirror specifications**

Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates:

- **make a subsection mirror via a process traceable to 500 mm deep mirrors**

Support System:

- **produce pre-Phase-A point designs for candidate primary mirror architectures;**
- **demonstrate specific actuation and vibration isolation mechanisms**

Mid/High Spatial Frequency Figure Error:

- 'null' polish a 1.5-m AMSD mirror & subscale deep core mirror to a < 6 nm rms zero-g figure at the 2°C operational temperature.

Segment Edges:

- **demonstrate an achromatic edge apodization mask**

Segment to Segment Gap Phasing:

- **develop models for segmented primary mirror performance; and**
- test prototype passive & active mechanisms to control gaps to ~ 1 nm rms.

Integrated Model Validation:

- **validate thermal model by testing** the AMSD and **deep core mirrors at 2°C**; and
- **validate mechanical models by static load test.**

9 Publications from Year 1

Stahl, H. Philip, *Overview and Recent Accomplishments of the Advanced Mirror Technology Development (AMTD) for large aperture UVOIR space telescopes project*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2013.

Stahl, H. Philip, W. Scott Smith, Marc Postman, *Engineering specifications for a 4 meter class UVOIR space telescope derived from science requirements*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2013.

Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X, 2013.

Matthews, Gary, et al, *Processing of a stacked core mirror for UV applications*, SPIE Conference on Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems, 2013.

Eng, Ron, et. al., *Cryogenic optical performance of a lightweighted mirror assembly for future space astronomical telescopes: correlation of optical test results and thermal optical model*, SPIE Conference on Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems, 2013.

Sivaramakrishnan, Anand, Alexandra Greenbaum, G. Lawrence Carr, and Randy J. Smith, *Calibrating apodizer fabrication techniques for high contrast coronagraphs on segmented and monolithic space telescopes*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2013.

Arnold, William et al, *Next generation lightweight mirror modeling software*, SPIE Conference on Optomechanical Engineering, 2013.

Arnold, William et al, *Integration of Mirror design with Suspension System using NASA's new mirror modeling software*, SPIE Conference on Optomechanical Engineering, 2013.

Gersh-Range, Jessica A., William R. Arnold, Mason A. Peck, and H. Philip Stahl, *A parametric finite-element model for evaluating segmented mirrors with discrete edgewise connectivity*, SPIE Proceedings 8125, 2011, DOI:10.1117/12.893469

Engineering Specifications

Sun Aug 25, 11:20 am: Stahl, H. Philip, W. Scott Smith, Marc Postman, Engineering specifications for a 4 meter class UVOIR space telescope derived from science requirements, UV/Optical/IR Space Telescopes and Instrumentation [8860-6]

Engineering Specifications Accomplishment

Derived from Science Requirements, Engineering Specifications for advanced normal-incidence monolithic and segmented mirror systems needed to enable both general astrophysics and ultra-high contrast observations of exoplanets missions as a function of potential launch vehicle and its inherent mass and volume constraints.

Table 2.1: Science Flow-down Requirements for a Large UVOIR Space Telescope

Science Question	Science Requirements	Measurements Needed	Requirements
Is there life elsewhere in Galaxy?	Detect at least 10 Earth-like Planets in HZ with 95% confidence.	High contrast (ΔMag > 25 mag) SNR=10 broadband (R = 5) imaging with IWA ~40 mas for ~100 stars out to ~20 parsecs.	≥ 8 meter aperture Stable 10^{-10} starlight suppression ~0.1 nm stable WFE per 2 hr ~1.3 to 1.6 mas pointing stability
	Detect presence of habitability and bio-signatures in the spectra of Earth-like HZ planets	High contrast (ΔMag > 25 mag) SNR=10 low-resolution (R=70-100) spectroscopy with an IWA ~ 40 mas; spectral range 0.3 – 2.5 microns; Exposure times <500 ksec	
What are star formation histories of galaxies?	Determine ages (~1 Gyr) and metallicities (~0.2 dex) of stellar populations over a broad range of galactic environments.	Color-magnitude diagrams of solar analog stars (Vmag~35 at 10 Mpc) in spiral, lenticular & elliptical galaxies using broadband imaging	≥ 8 meter aperture Symmetric PSF 500 nm diffraction limit 1.3 to 1.6 mas pointing stability
What are kinematic properties of Dark Matter	Determine mean mass density profile of high M/L dwarf Spheroidal Galaxies	0.1 mas resolution for proper motion of ~200 stars per galaxy accurate to ~20 μas/yr at 50 kpc	
How do galaxies & IGM interact and affect galaxy evolution?	Map properties & kinematics of intergalactic medium over contiguous sky regions at high spatial sampling to ~10 Mpc.	SNR = 20 high resolution UV spectroscopy (R = 20,000) of quasars down to FUV mag = 24, survey wide areas in < 2 weeks	≥ 4 meter aperture 500 nm diffraction limit Sensitivity down to 100 nm wavelength.
How do stars & planets interact with interstellar medium?	Measure UV Ly-alpha absorption due to Hydrogen "walls" from our heliosphere and astrospheres of nearby stars	High dynamic range, very high spectral resolution (R = 100,000) UV spectroscopy with SNR = 100 for V = 14 mag stars	
How did outer solar system planets form & evolve?	UV spectroscopy of full disks of solar system bodies beyond 3 AU from Earth	SNR = 20 - 50 at spectral resolution of R ~10,000 in FUV for 20 AB mag	

Table 3.1: Science Requirement to Technology Need Flow Down

Science	Mission	Constraint	Capability	Technology Challenge
Sensitivity	Aperture	EELV 5 m Fairing, 6.5 mt to SEL2	4 m Monolith	4 m, 200 Hz, 60 kg/m²
				4 m support system
			8 m Segmented	2 m, 200 Hz, 15 kg/m²
				8 m deployed support
		HLLV-Medium 10 m Fairing, 40 mt to SEL2	8 m Monolith	8 m, <100Hz, 200kg/m²
				8 m, 10 mt support
			16 m Segmented	2-4m, 200Hz, 50kg/m2
				16 m deployed support
		HLLV-Heavy 10 m Fairing, 60 mt to SEL2	8 m Monolith	8m, <100Hz, 480kg/m2
				8 m, 20 mt support
			16 m Segmented	2-4m, 200Hz, 120kg/m²
				16 m deployed support
	2 hr Exposure	Thermal 280K ± 0.5K 0.1K per 10min	< 5 nm rms per K	low CTE material
			> 20 hr thermal time constant	thermal mass
		Dynamics TBD micro-*g*	< 5 nm rms figure	passive isolation
				active isolation
	Reflectance	Substrate Size	> 98% 100-2500 nm	Beyond Scope
High Contrast	Diffraction Limit	Monolithic	< 10 nm rms figure	mid/high spatial error fabrication & test
		Segmented	< 5 nm rms figure	
			< 2 mm edges	edge fabrication & test
			< 1 nm rms phasing	passive edge constraint
				active align & control

Telescope Performance Requirements

Telescope Specifications depend upon the Science Instrument.

Telescope Specifications have been defined for 3 cases:

- 4 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an External Occulter

WFE Specification is before correction by a Deformable Mirror

WFE/EE Stability and MSF WFE are the stressing specifications

Specifications have not been defined for a Visible Nulling Coronagraph or phase type coronagraph.

8m Telescope Requirements for Coronagraph

On-axis Monolithic 8-m Telescope with 3λ/D Coronagraph			
Performance Parameter	Specification	Source	Comments
Maximum total system rms WFE	38 nm	Diffraction limit (80% Strehl ratio at 500 nm)	
Encircled Energy Fraction (EEF)	80% within 16 mas at 500 nm	HST spec, modified to larger aperture and slightly bluer wavelength	Vary < 5% across 4 arcmin FOV
EEF stability	<2%	JWST	
WFE stability over 20 minutes	~1.5 nm	λ/500 at 760 nm	
PM rms surface error	5 - 10 nm	HST / ATLAST studies	
Pointing stability (jitter)	~2 mas	Guyon, scaled from HST	~ 0.5 mas floor determined by stellar angular diameter.
Mid-frequency WFE	< 20 nm	HST	

Large-Aperture, Low-Areal Density, High-Stiffness Mirror Substrates

Tues Aug 27, 8:40 am: Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X [8838-23]

Tues Aug 27, 11:10 am: Matthews, Gary, et al, *Processing of a stacked core mirror for UV applications*, SPIE Conference on Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems [8837-10]

Large Substrate: Technical Challenge

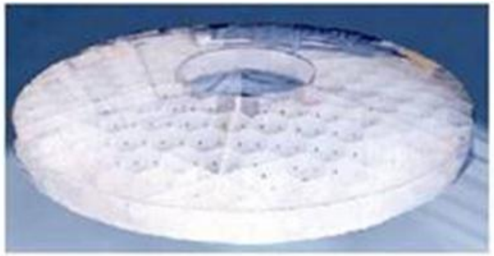
Future large-aperture space telescopes (regardless of monolithic or segmented) need ultra-stable mechanical and thermal performance for high-contrast imaging.

This requires larger, thicker, and stiffer substrates.

Current launch vehicle capacity also requires low areal density.

State of the Art is

- ATT Mirror: 2.4 m, 3-layer, 0.3 m deep, 60 kg/m2 substrate
- Also 1.4 m AMSD and 1 m Kepler



ITT's 2.4m ATT Demonstration Mirror

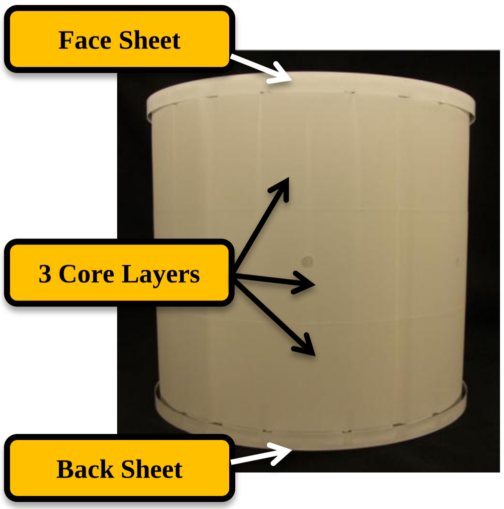
Large Substrate: Achievements

- Successfully demonstrated a new fabrication process (stacked core low-temperature fusion).
  - New process offers significant cost and risk reduction over incumbent process. It is difficult (and expensive) to cut a deep-core substrate to exacting rib thickness requirements. Current SOA is ~300 mm on an expensive custom machine. But, < 130 mm deep cores can be done on commercial machines.
- Extended state of the art for deep core mirrors from less than 300 mm to greater than 400 mm.
- Successfully 're-slumped' a ULE fused substrate.
  - This is interesting because it allows generic substrates to be assembled and place in inventory for re-slumping to a final radius of curvature.

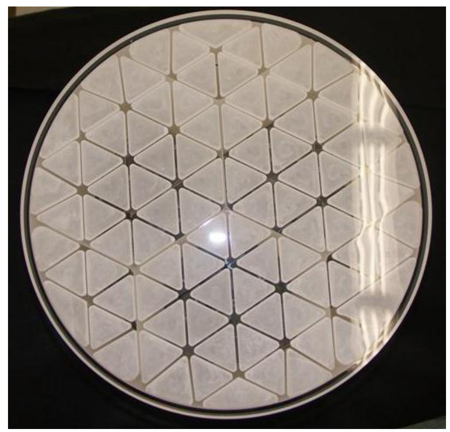
43 cm Deep Core Mirror

Exelis successfully demonstrated 5-layer 'stack & fuse' technique which fuses 3 core structural element layers to front & back faceplates.

Made 43 cm 'cut-out' of a 4 m dia, > 0.4 m deep, 60 kg/m^2 mirror substrate.



Post-Fusion Side View
3 Core Layers and Vent Hole Visible



Post-Fusion Top View
Pocket Milled Faceplate

Post Slump:
2.5 meter Radius of Curvature

This technology advance leads to stiffer 2 to 4 to 8 meter class substrates at lower cost and risk for monolithic or segmented mirrors.

Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X, 2013.

Mid/High Spatial Frequency Figure Error

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Tues Aug 27, 11:30 am: Eng, Ron, et. al., *Cryogenic optical performance of a lightweighted mirror assembly* [8837-11]

Mid/High Spatial Frequency Figure Error

Technical Challenge:

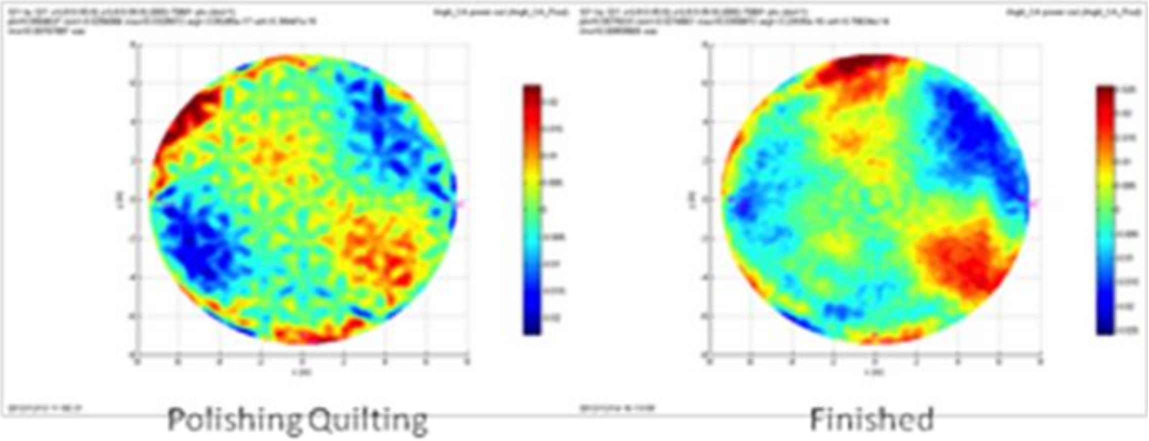
- High-contrast imaging requires a very smooth mirror (< 10 nm rms)
- Mid/High spatial errors (zonal & quilting) can introduce artifacts
- DMs correct low-spatial errors, not mid/high spatial errors
- On-orbit thermal environment can stress mirror introducing error

Achievements:

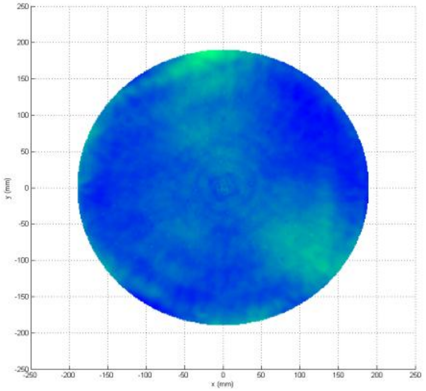
- AMTD partner Exelis designed facesheet to minimize mid/high spatial frequency quilting error from polishing pressure and thermal stress.
- Exelis ion polishing process produced 5.4 nm rms surface
- Thermal test showed no measurable cryo-deformation or quilting

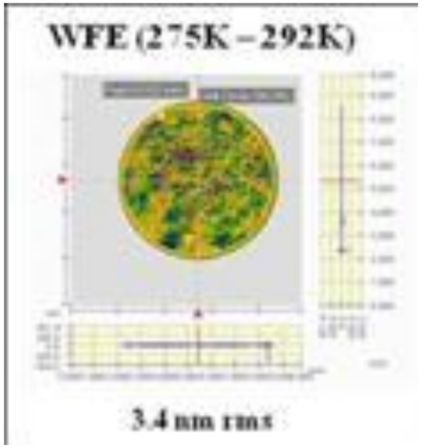
Mid/High Spatial Frequency Error

Exelis polished 43 cm deep-core mirror to a zero-gravity figure of 5.5 nm rms using ion-beam figuring to eliminate quilting.



MSFC tested 43 cm mirror from 250 to 300K. Its thermal deformation was insignificant (smaller than 4 nm rms ability to measure the shape change)





Integrated Model Validation

Tues Aug 27, 11:30 am: Eng, Ron, et. al., *Cryogenic optical performance of a lightweighted mirror assembly for future space astronomical telescopes: correlation of optical test results and thermal optical model*, Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems, [8837-11]

Integrated Model Validation

Technical Challenge:

- On-orbit performance is determined by mechanical & thermal stability
- As future systems become larger, compliance cannot be 100% tested
- Verification will rely on sub-scale tests & validated high fidelity models

Achievement:

- Developed new opto-mechanical tool to create high-fidelity models
- Created models to predict gravity sag & 2C thermal gradients
- Validated models by interferometric and <u>thermal imaging</u> test

Deep Core Thermal Model

Thermal Model of 43 cm deep core mirror generated and validate by test.

43 cm deep core mirror tested from 250 to 300K

Test Instrumentation

- 4D Instantaneous Interferometer to measure surface Wavefront Error
- InSb Micro-bolometer to measure front surface temperature gradient to 0.05C
- 12 Thermal Diodes.

Figure 8: 43-cm mirror test setup.

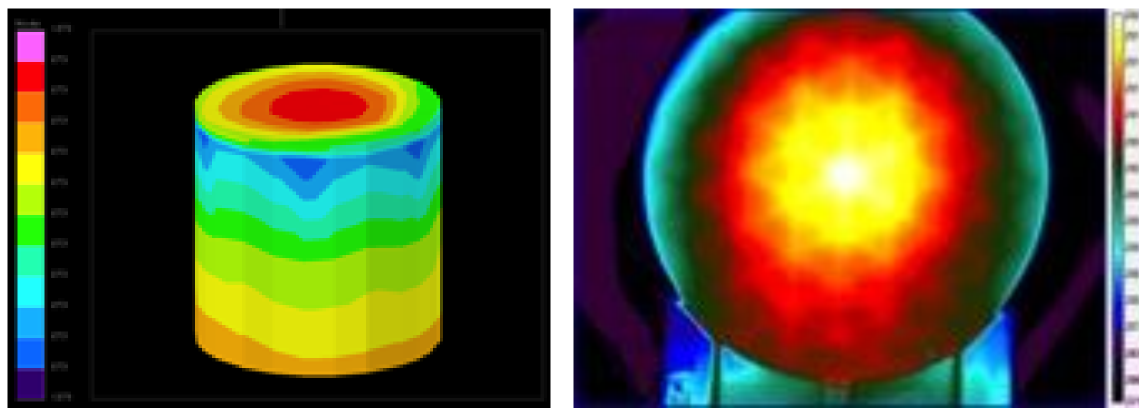


Figure 9: Predicted Thermal Model (left) vs. Measure Performance (right)

NOTE: This was first ever XRCF test using thermal imaging to monitor temperature

Segment Edges

Mon Aug 2, 5:30 pm Poster: Sivaramakrishnan, Anand, et. al., *Calibrating apodizer fabrication techniques for high contrast coronagraphs on segmented and monolithic space telescopes*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation [8860-32]

Segment Edges

Technical Challenge:

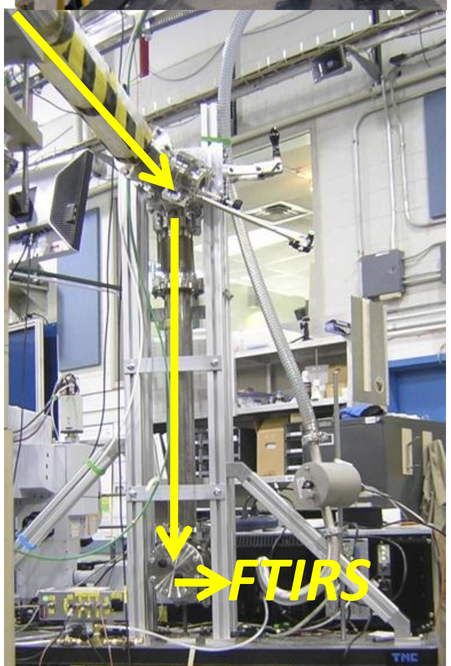
- Segmented primary mirror edge quality impacts PSF for high-contrast imaging applications and contributes to stray light noise.
- Diffraction from secondary mirror obscuration and support structure also impacts performance.

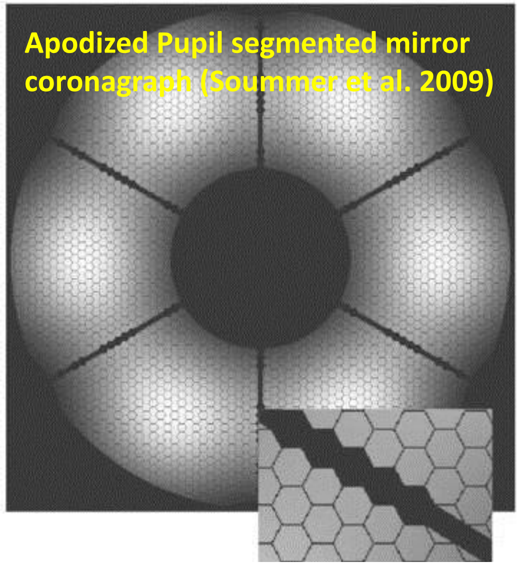
Achievement

- AMTD partner STScI successfully demonstrated an achromatic edge apodization process to minimize segment edge diffraction and straylight on high-contrast imaging PSF.

Primary mirror segment gap apodization in the optical

A. Sivaramakrishnan, G. L. Carr, R. Smith, X. X. Xi, & N. T. Zimmerman





Apodization mitigates segment gaps

- Achromatic apodization in collimated space

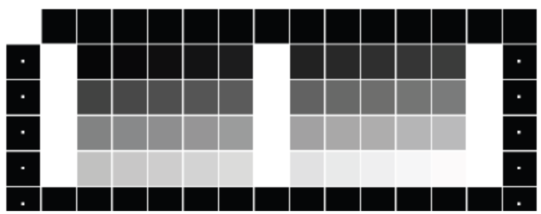
Tolerancing can be tight

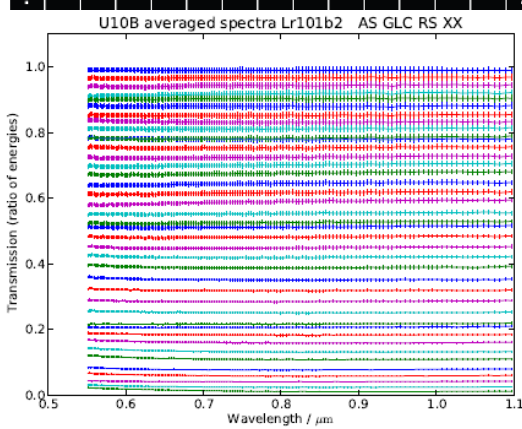
- Gemini Planet Imager (1.1-2.4 um) – 0.5% accuracy req.
- UVOIR space coronagraphy - 0.55 – 1.1 um

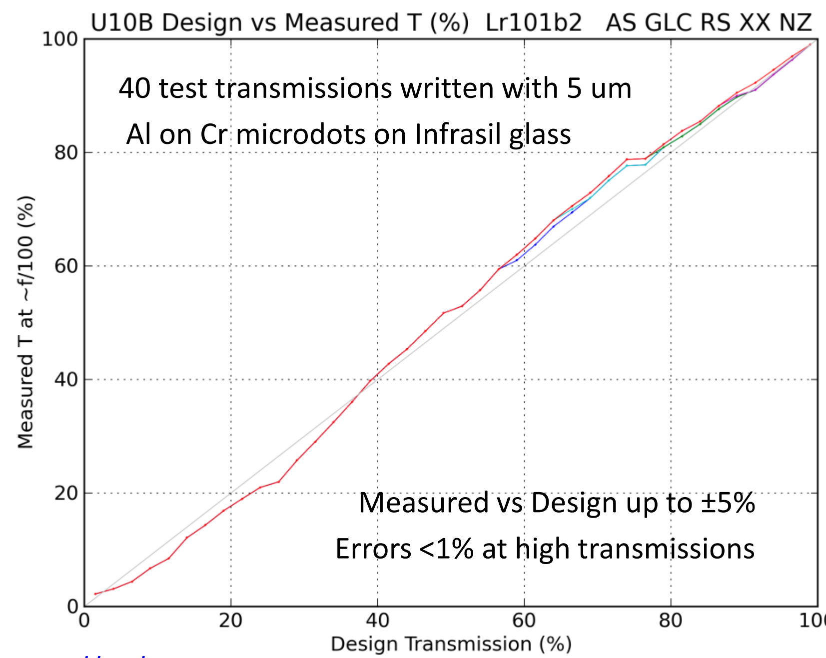
Metal-on-glass dots look OK

Next

- Develop & confirm on reflective surfaces
- Reqs. on accuracy, reflectivity, absorption/, polarization?
- Use larger dots to reduce non-linearity







Use of the National Synchrotron Light Source, Brookhaven National Laboratory, was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-98CH10886.

Support System

Wed Aug 28, 5:00 pm: Arnold, William et al, Next generation lightweight mirror modeling software, Optomechanical Engineering 2013 [8836-15]

Wed Aug 28, 5:20 pm: Arnold, William et al, Integration of Mirror design with Suspension System using NASA's new mirror modeling software, Optomechanical Engineering 2013 [8836-17]

Support System

Technical Challenge:

- Large-aperture mirrors require large support systems to survive launch & deploy on orbit in a stress-free and undistorted shape.

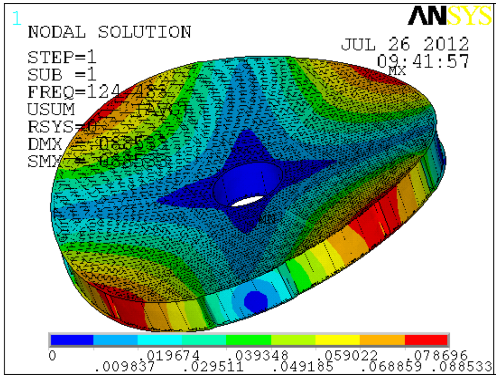
Accomplishments:

- Developed a new modeler tool for ANSYS which can produce 400,000-element models in minutes.
- Tool facilitates transfer of high-resolution mesh to mechanical & thermal analysis tools.
- Used our new tool to compare pre-Phase-A point designs for 4-meter and 8-meter monolithic primary mirror substrates and supports.

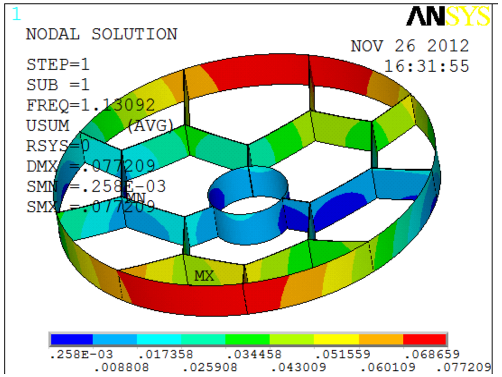
Design Tools and Point Designs

AMTD has developed a powerful tool which quickly creates monolithic or segmented mirror designs; and analyzes their static & dynamic mechanical and thermal performance.

Point Designs: AMTD has used these tools to generate Pre-Phase-A point designs for 4 & 8-m mirror substrates.



Free-Free 1st Mode: 4 m dia 40 cm thick substrate



Internal Stress: 4 m dia with 6 support pads

Support System: AMTD has used these tools to generate Pre-Phase-A point designs for 4-m mirror substrate with a launch support system.

Monolithic Substrate Point Designs

4-m designs are mass constrained to 720 kg for launch on EELV

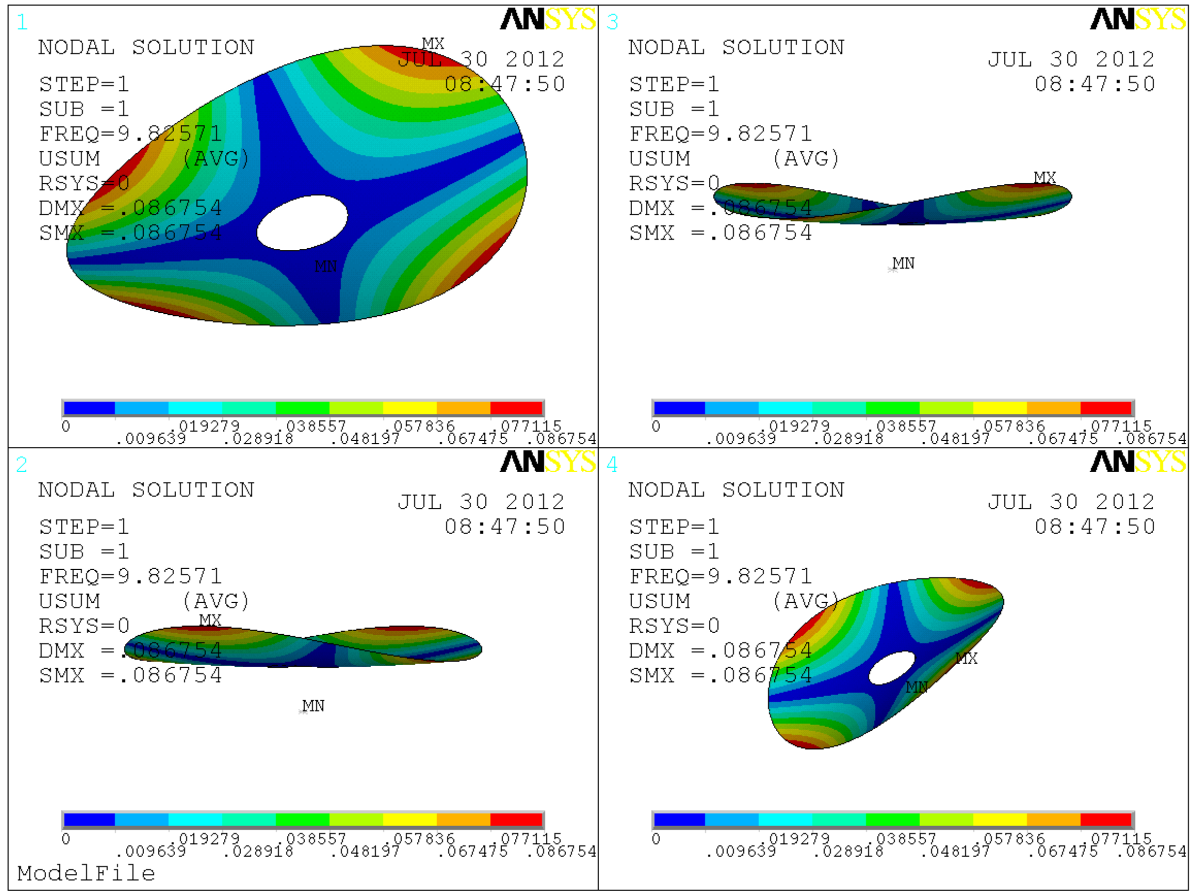
8-m designs are mass constrained to 22 mt for launch on SLS

Trade Study Concept #1: 4 m Solid

Design:

Diameter	4 meters
Thickness	26.5 mm
Mass	716 kg
First Mode	9.8 Hz

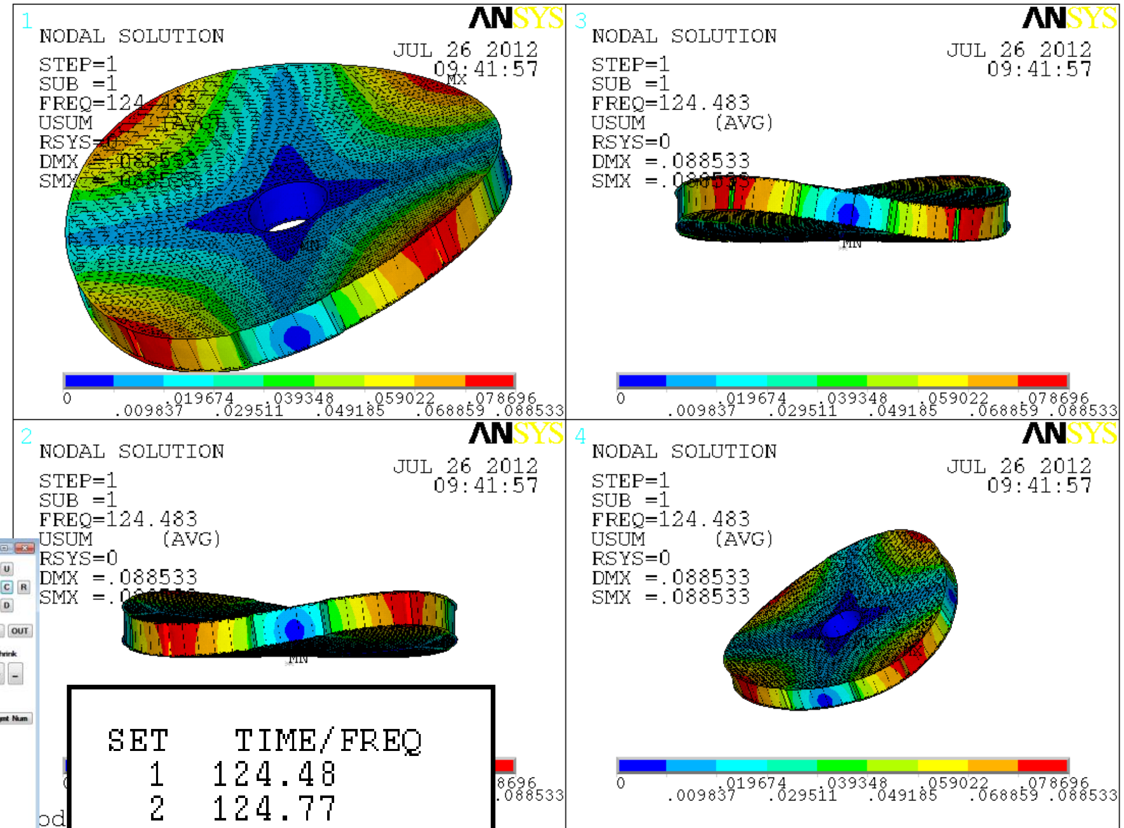
SET	TIME/FREQ
1	9.8257
2	9.8257
3	23.548
4	23.552
5	41.021
6	41.021
7	62.123
8	62.123
9	86.807
10	86.807

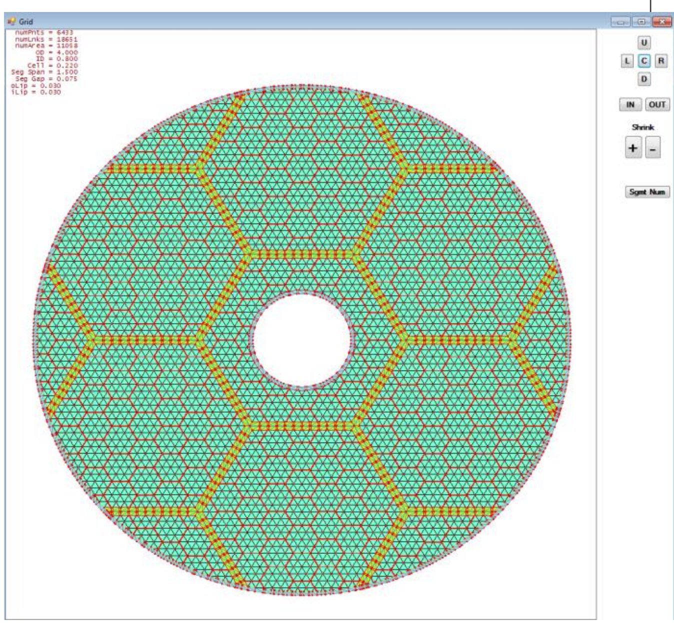


Trade Study Concept #2: 4 meter Lightweight

Design:

Diameter	4 meters
Thickness	410 mm
Facesheet	3 mm
Mass	621 kg
First Mode	124.5 Hz





SET	TIME/FREQ
1	124.48
2	124.77
3	199.39
4	257.85
5	275.88
6	321.22
7	321.60
8	350.07
9	350.08
10	350.33

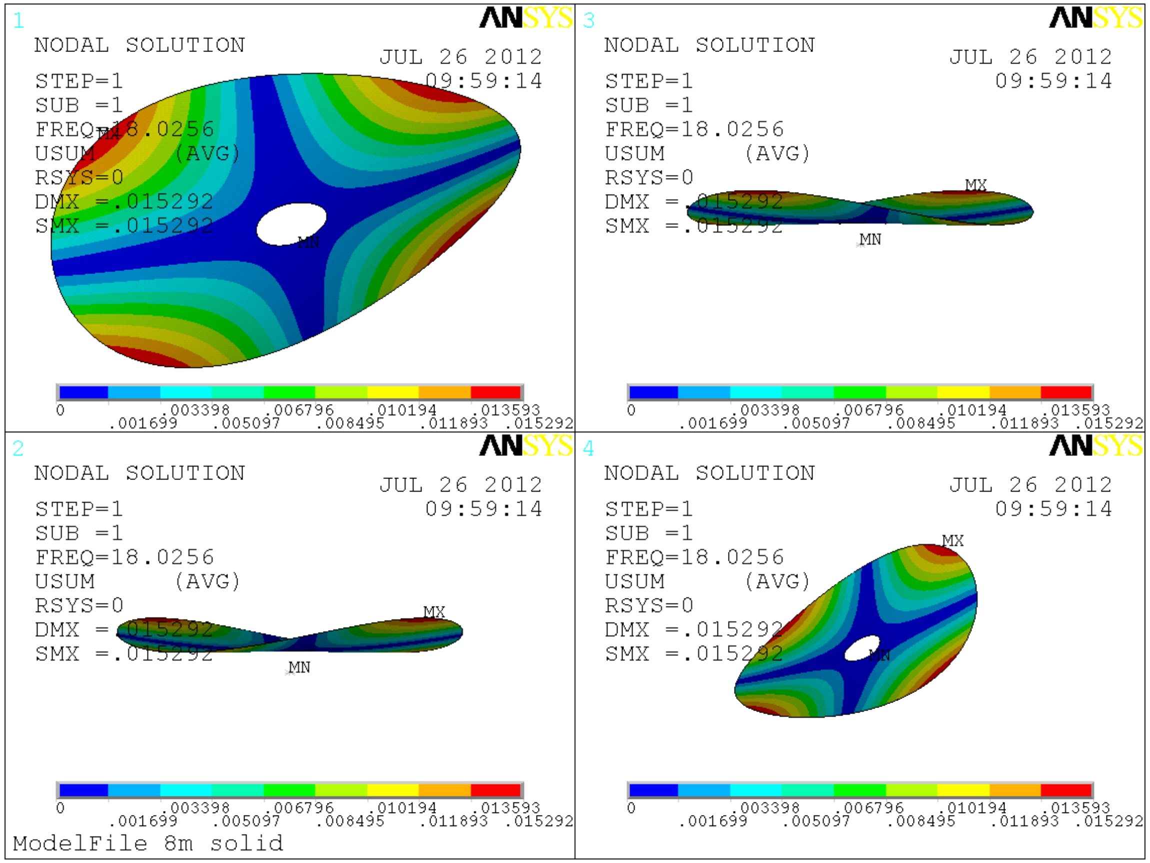
Trade Study Concept #3: 8 meter Solid 22 MT

Design:

Diameter	8 meter
Thickness	200 mm
Mass	21,800 kg
First Mode	18 Hz

Same as ATLAST Study

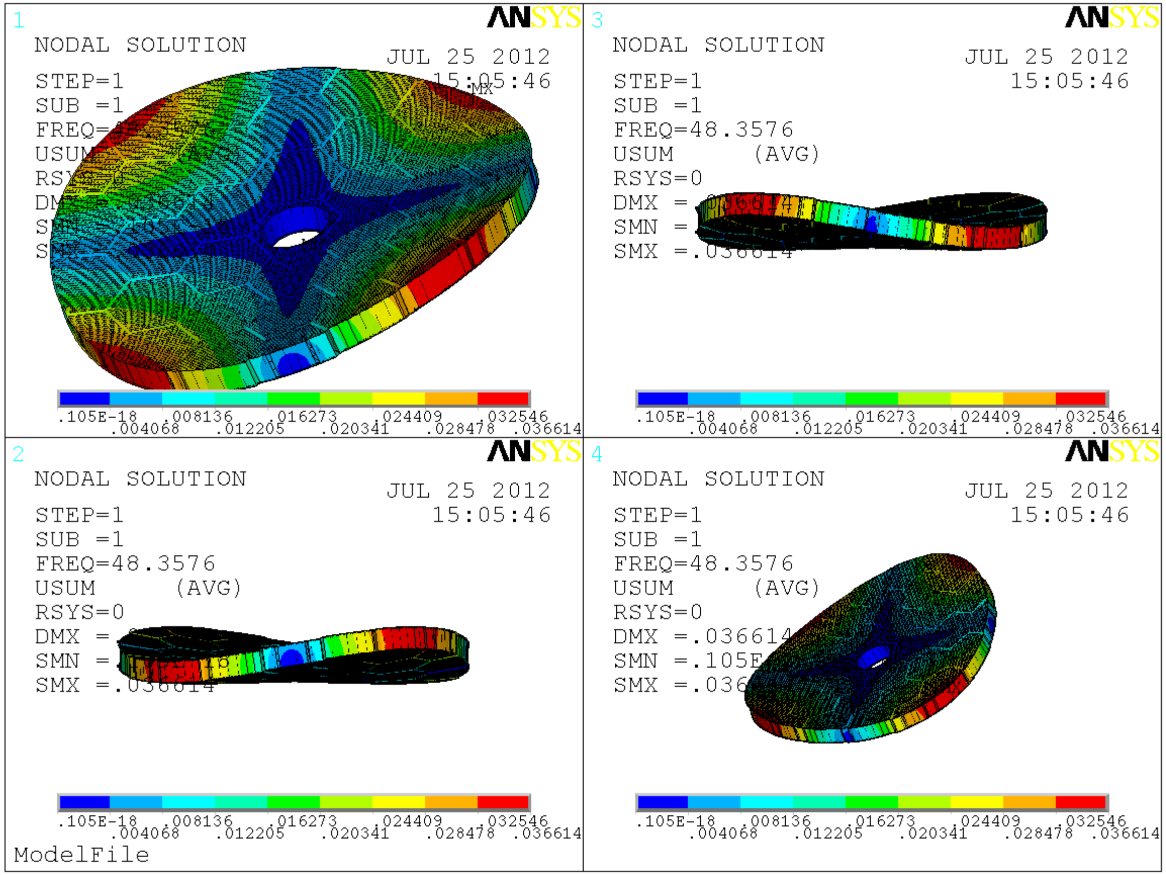
SET	TIME/FREQ
1	18.026
2	18.035
3	42.449
4	42.452
5	47.827
6	74.041
7	74.045
8	75.174
9	75.176
10	112.96



Trade Study Concept #4: 8 meter Lightweight

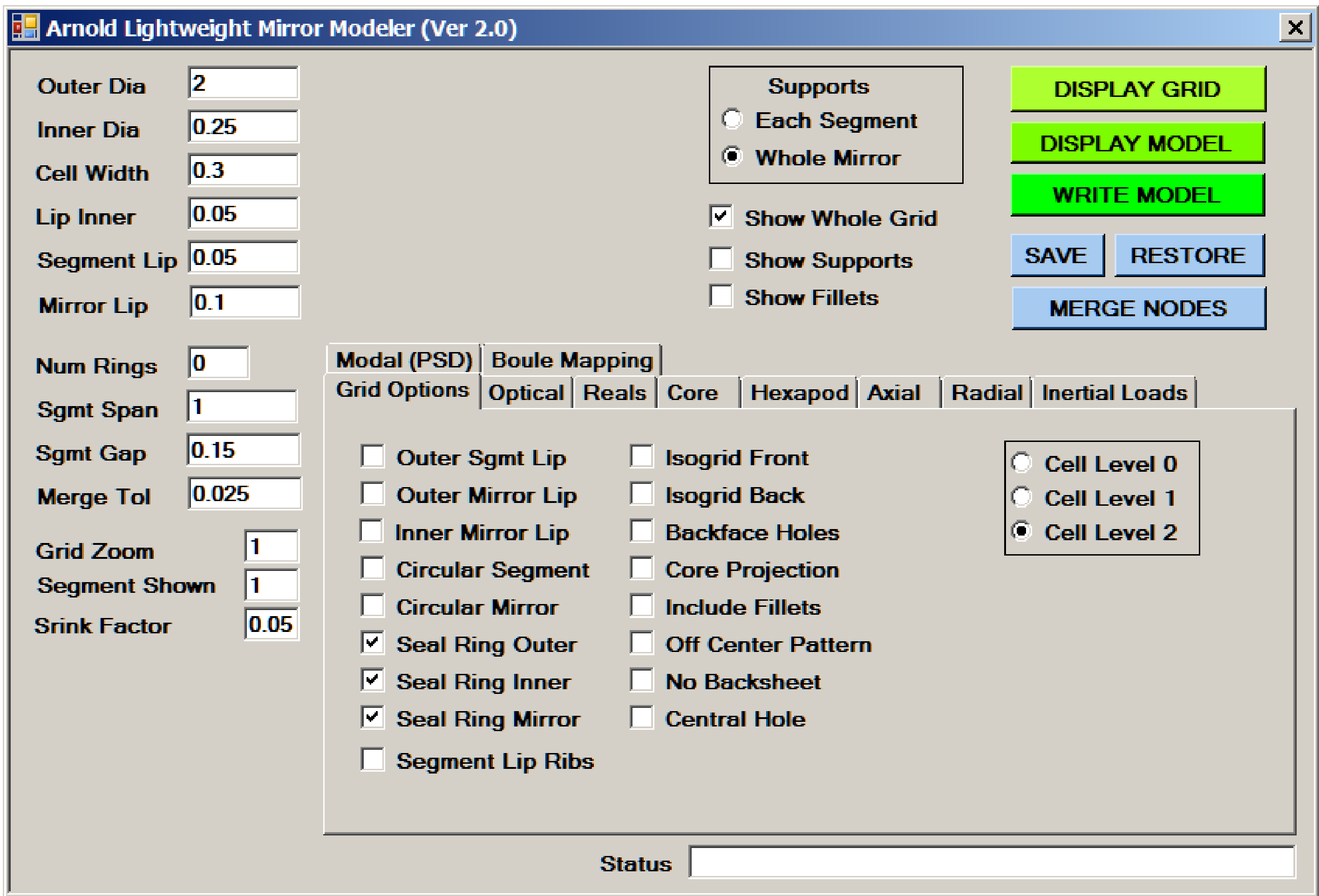
Design:

Diameter	8 meter
Thickness	510 mm
Facesheet	7 mm
Mass	3,640 kg
First Mode	48.4 Hz

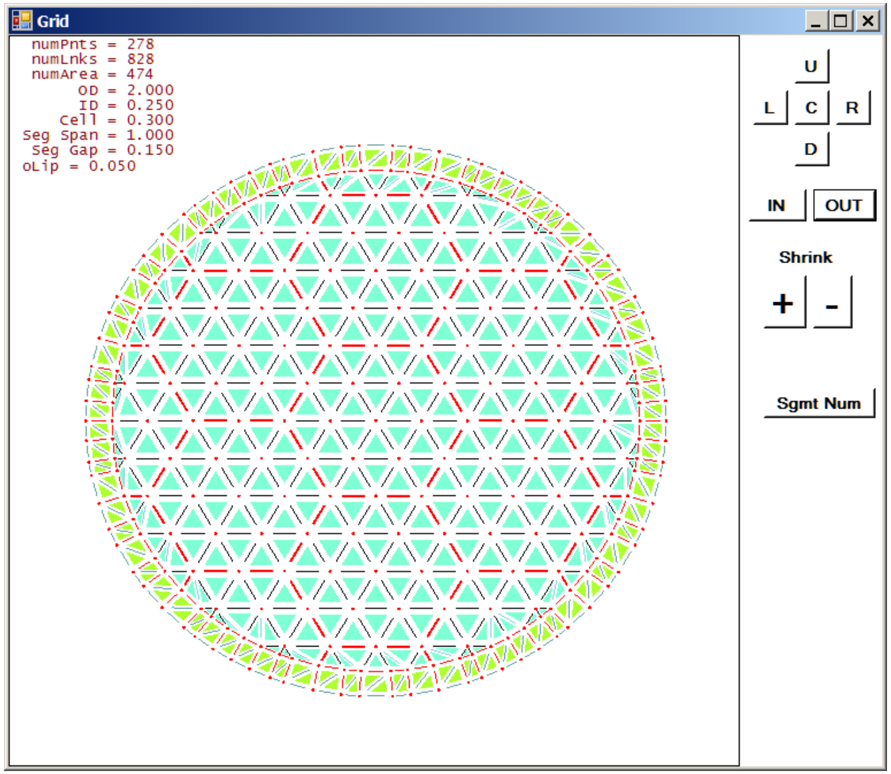


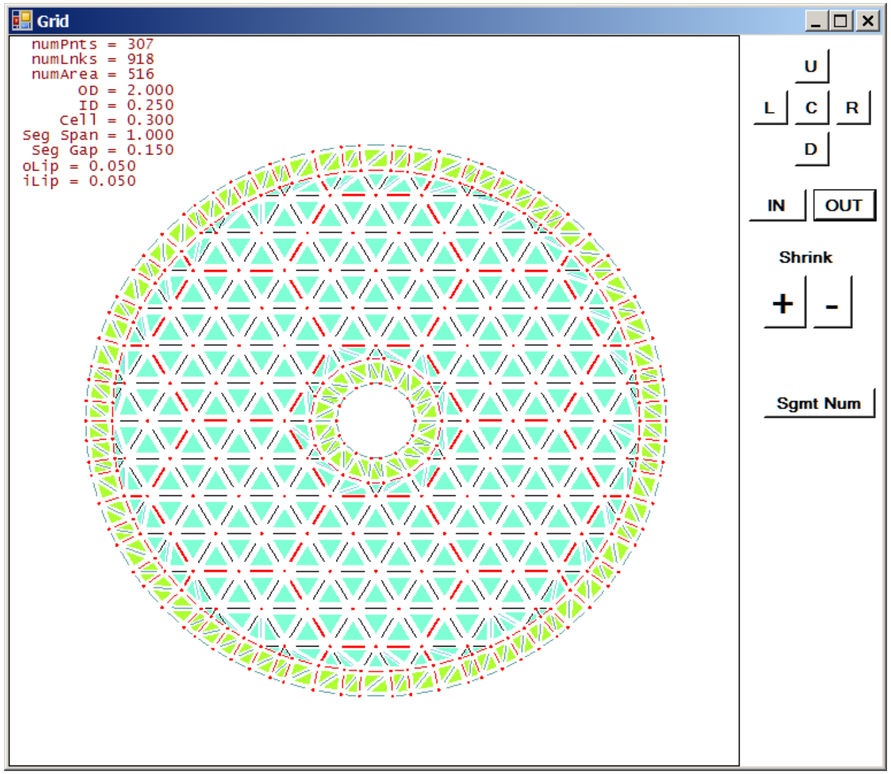
Modeling Tool

Program Control Window

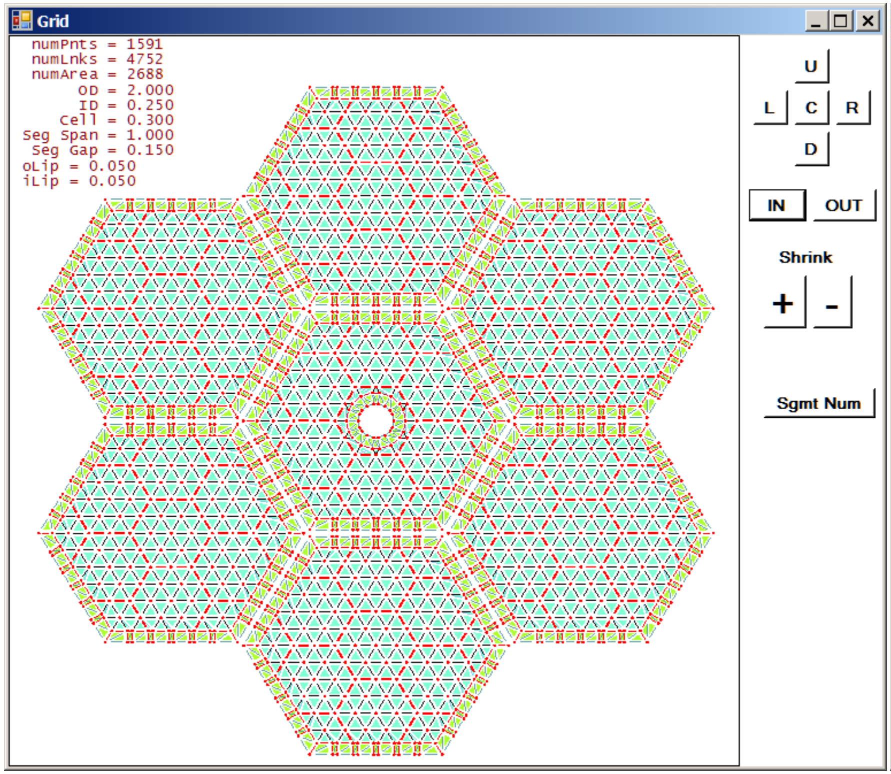


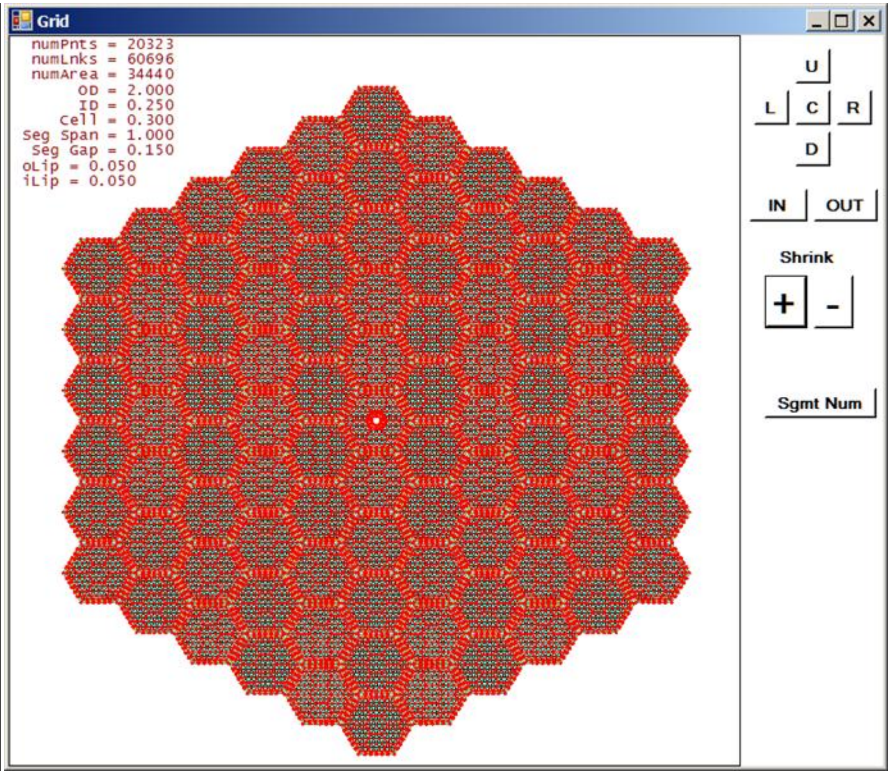
Monolithic Mirrors





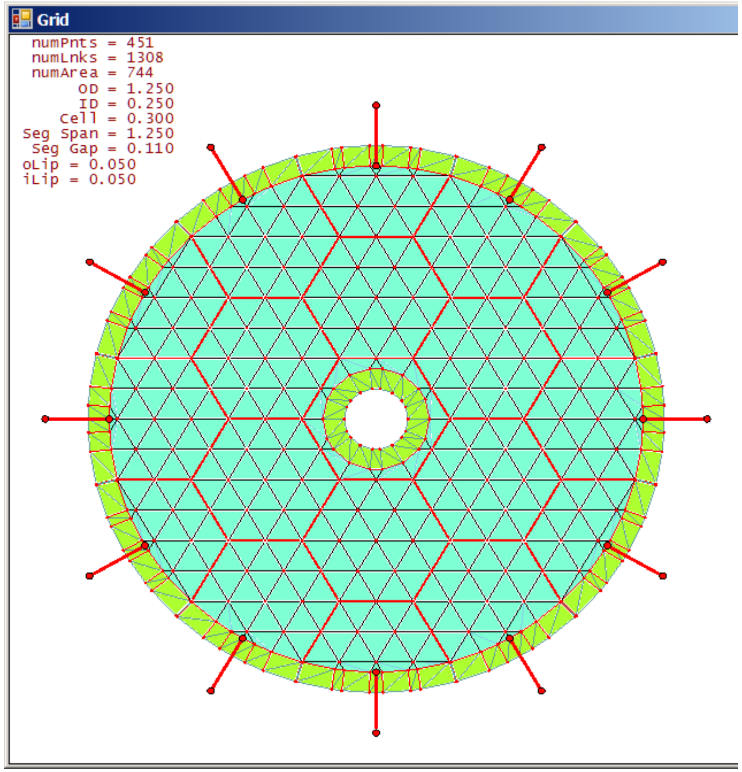
Segmented Mirrors





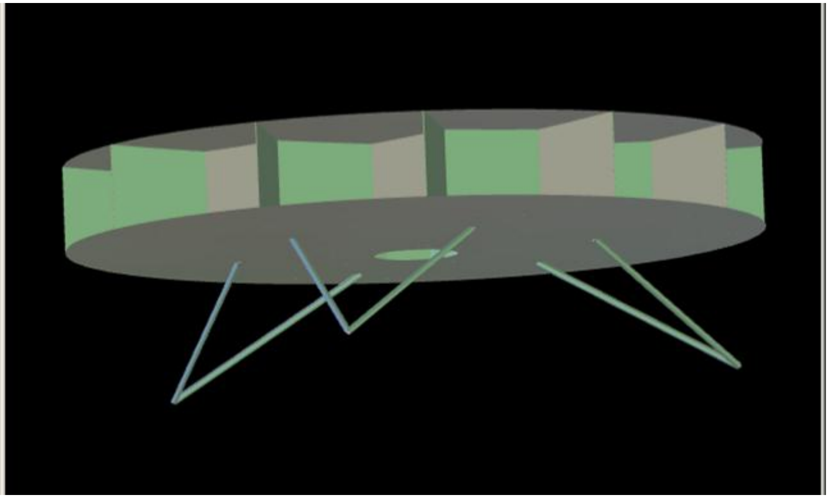
Support Systems

Radial



Axial

Hexapod



Segment to Segment Gap Phasing

Segment to Segment Gap Phasing

Technical Challenge:

- To avoid speckle noise which can interfere with exo-planet observation, Internal coronagraphs require segment to segment dynamic co-phasing error < 10 pm rms between WFSC updates.

Achievements:

- Built a Delron plastic pendulum to investigated utility of correlated magnetic interfaces.
- Correlated magnetic interface provided only marginally improved dampening over conventional magnets.
- Given the inability to reduce dynamic below the required level, we plan no further investigation of this approach.

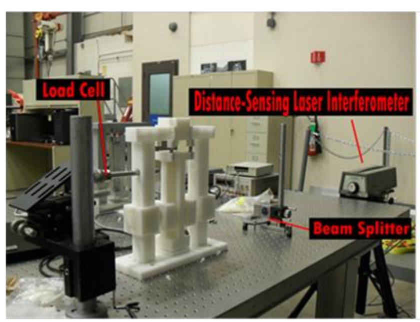


Figure 6: Delron Pendulum Test Setup

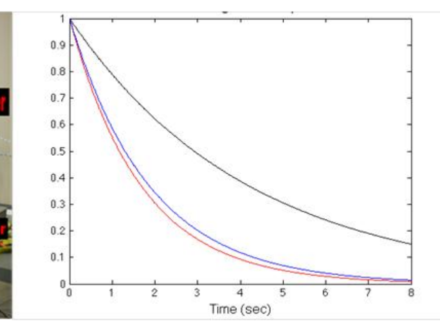


Figure 7: Oscillation Amplitude vs. Time for Unconstrained (black), Conventional Magnetic Interface (blue), and Correlated Magnetic Interface (red)

Conclusions

AMTD uses a science-driven systems engineering approach to define & execute a long-term strategy to mature technologies necessary to enable future large aperture space telescopes.

Because we cannot predict the future, we are pursuing multiple technology paths including monolithic & segmented mirrors.

Assembled outstanding team from academia, industry & government; experts in science & space telescope engineering.

Derived engineering specifications from science measurement needs & implementation constraints.

Maturing 6 critical technologies required to enable 4 to 8 meter UVOIR space telescope mirror assemblies for both general astrophysics & ultra-high contrast exoplanet imaging.

AMTD achieving all its goals & accomplishing all its milestones

BACKUP

Requirements for a large UVOIR space telescope are derived directly from fundamental Science Questions

Table 2.1: Science Flow-down Requirements for a Large UVOIR Space Telescope

Science Question	Science Requirements	Measurements Needed	Requirements
Is there life elsewhere in Galaxy?	Detect at least 10 Earth-like Planets in HZ with 95% confidence.	High contrast (ΔMag > 25 mag) SNR=10 broadband (R = 5) imaging with IWA ~40 mas for ~100 stars out to ~20 parsecs.	≥ 8 meter aperture Stable 10^{-10} starlight suppression ~0.1 nm stable WFE per 2 hr ~1.3 to 1.6 mas pointing stability
	Detect presence of habitability and bio-signatures in the spectra of Earth-like HZ planets	High contrast (ΔMag > 25 mag) SNR=10 low-resolution (R=70-100) spectroscopy with an IWA ~ 40 mas; spectral range 0.3 – 2.5 microns; Exposure times <500 ksec	
What are star formation histories of galaxies?	Determine ages (~1 Gyr) and metallicities (~0.2 dex) of stellar populations over a broad range of galactic environments.	Color-magnitude diagrams of solar analog stars (Vmag~35 at 10 Mpc) in spiral, lenticular & elliptical galaxies using broadband imaging	≥ 8 meter aperture Symmetric PSF 500 nm diffraction limit 1.3 to 1.6 mas pointing stability
What are kinematic properties of Dark Matter	Determine mean mass density profile of high M/L dwarf Spheroidal Galaxies	0.1 mas resolution for proper motion of ~200 stars per galaxy accurate to ~20 µas/yr at 50 kpc	
How do galaxies & IGM interact and affect galaxy evolution?	Map properties & kinematics of intergalactic medium over contiguous sky regions at high spatial sampling to ~10 Mpc.	SNR = 20 high resolution UV spectroscopy (R = 20,000) of quasars down to FUV mag = 24, survey wide areas in < 2 weeks	≥ 4 meter aperture 500 nm diffraction limit Sensitivity down to 100 nm wavelength.
How do stars & planets interact with interstellar medium?	Measure UV Ly-alpha absorption due to Hydrogen "walls" from our heliosphere and astrospheres of nearby stars	High dynamic range, very high spectral resolution (R = 100,000) UV spectroscopy with SNR = 100 for V = 14 mag stars	
How did outer solar system planets form & evolve?	UV spectroscopy of full disks of solar system bodies beyond 3 AU from Earth	SNR = 20 - 50 at spectral resolution of R ~10,000 in FUV for 20 AB mag	

Technology Challenges are derived directly from Science & Mission Requirements, and Implementation Constraints

Table 3.1: Science Requirement to Technology Need Flow Down

Science	Mission	Constraint	Capability	Technology Challenge
Sensitivity	Aperture	EELV 5 m Fairing, 6.5 mt to SEL2	4 m Monolith	4 m, 200 Hz, 60 kg/m^2
				4 m support system
			8 m Segmented	2 m, 200 Hz, 15 kg/m^2
				8 m deployed support
		HLLV-Medium 10 m Fairing, 40 mt to SEL2	8 m Monolith	8 m, <100Hz, 200kg/m^2
				8 m, 10 mt support
			16 m Segmented	2-4m, 200Hz, 50kg/m2
				16 m deployed support
		HLLV-Heavy 10 m Fairing, 60 mt to SEL2	8 m Monolith	8m, <100Hz, 480kg/m2
				8 m, 20 mt support
			16 m Segmented	2-4m, 200Hz, 120kg/m^2
				16 m deployed support
	2 hr Exposure	Thermal 280K ± 0.5K 0.1K per 10min	< 5 nm rms per K	low CTE material
			> 20 hr thermal time constant	thermal mass
		Dynamics TBD micro-*g*	< 5 nm rms figure	passive isolation
				active isolation
	Reflectance	Substrate Size	> 98% 100-2500 nm	Beyond Scope
High Contrast	Diffraction Limit	Monolithic	< 10 nm rms figure	mid/high spatial error fabrication & test
		Segmented	< 5 nm rms figure	
			< 2 mm edges	edge fabrication & test
			< 1 nm rms phasing	passive edge constraint
				active align & control